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COSMIC RAY ANTIMATTER: IS IT PRIMARY OR SECONDARY?

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ABSTRACT

We examine the relative merits and difficulties of the primary and secondary origin hypotheses for the observed cosmic-ray antiprotons, including the new low-energy measurement of Buffington, et al. We conclude that the cosmic-ray antiproton data may be strong evidence for antimatter galaxies and baryon symmetric cosmology. The present $\bar{p}$ data are consistent with a primary extragalactic component having $\bar{p}/p \simeq 3.2 \pm 0.7 \times 10^{-4}$ independent of energy.

1. Introduction Measurements of cosmic-ray antiprotons can give us important information about cosmic ray propagation and also provide a test for primary cosmological antimatter[1]. Buffington, et al.[2], observing at energies well below the secondary cutoff, appear to see just such a signal of primary antiprotons. Data on $\bar{p}$ fluxes at higher energies[3] give measured values a factor of 4-10 above the fluxes expected for a standard "leaky box" type propagation model with the primaries passing through ~ 5 g/cm^2 of material[4,5]. Because a new basis now exists for reconsidering the primary hypothesis in a baryon symmetric cosmology[6], we reconsider here the question of primary versus secondary origin of cosmic ray antiprotons.

Gaisser and Maurer[4] made the first reliable predictions of the $\bar{p}/p$ ratio and used the leaky box model with a mean escape length of 5 g/cm^2 of hydrogen. Their result is consistent with later predictions[4] except that of Badhwar et al.[7] which was shown to be in error by Tan and Ng[4]. All these predictions show a cutoff in the secondary $\bar{p}$ spectrum for kinetic energies below ~ 1 GeV, which is a basic feature of the kinematics of the $\bar{p}$ production process. The pathlength distribution for the "nested leaky box model"[8] is truncated at low pathlengths but has an exponential tail. Such a model would predict a $\bar{p}/p$ ratio lower than that for the leaky box model and give a worse fit to the data.

2. The Closed Galaxy Model The closed galaxy model[9] gives a higher $\bar{p}/p$ ratio than the leaky box model. In it the sources of cosmic rays are located in the spiral arms of the Galaxy, from which they slowly leak out into the halo. The outer boundary of the halo constitutes a closed box from which cosmic rays cannot escape. Depletion of cosmic rays in the halo is then solely due to nuclear interactions and energy losses. The halo thus contains an "old component" while the spiral arms also contain a "young component" of cosmic rays. In this model, cosmic ray antiprotons are mainly produced by protons of the old component in the halo which have traversed ~ 100 g/cm^2 of material (rather than ~ 5 g/cm^2) giving an increased secondary $\bar{p}$ flux. An important parameter of the closed galaxy model is K, the ratio of the mass of gas in the galaxy as a whole to that in the spiral arms. The rate of production of antiprotons in the halo has been calculated for values of K ranging from 50 to 500. We show the resulting $\bar{p}/p$ ratios in Figure 1. Details of the calculation, which takes account of $\bar{p}$ annihil-

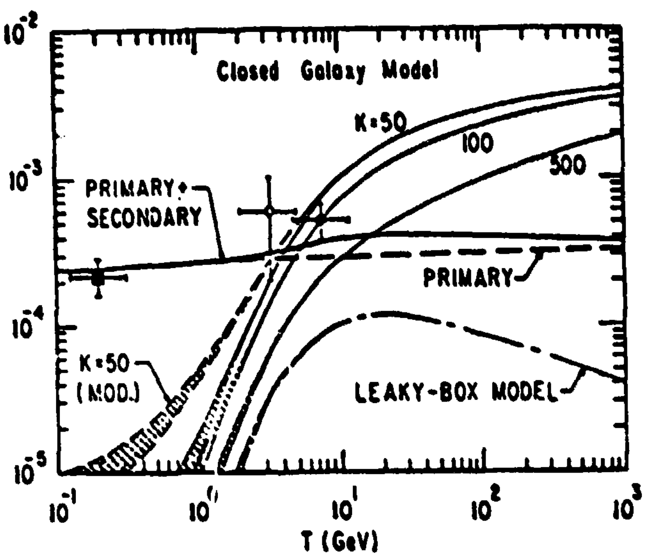

Fig. 1: The predicted p̄/p ratio for closed galaxy and leaky box models compared with the observations. The curve K=50 Mod indicates the effect of solar modulation with a mean energy loss of 600 MeV on the closed galaxy model prediction for K=50. (■) Buffington, et al.[2]; (○) Bogomolov et al.[3]; (●) Golden et al.[3]. The heavy line shows the effect of adding an extragalactic p̄ component to the leaky box model.

ation, ionization energy losses, the redistribution in energy of antiprotons in nuclear interactions, and nuclear target effects, are given by Protheroe[5].

As can be seen from the figure, the closed galaxy model predictions are compatible with the high energy data but predict a p̄ flux which, although significantly higher than for the leaky box model, is still more than a decade below that observed by Buffington, et al. At these energies, solar modulation is important and must be considered. If protons and antiprotons suffer the same energy losses in the heliosphere, then the p̄/p ratios of Fig. 1 should just be shifted to the appropriate lower energies[10]. This has been done for the closed galaxy model prediction (K=50) for a mean energy loss of 600 MeV appropriate to near solar maximum conditions[11]. The modulated prediction is shown in Figure 1 and is still more than an order of magnitude below the data. A more accurate treatment of the modulation process is unlikely to account for this discrepancy. There are various problems associated with the closed galaxy model in any case. It cannot account for the shape of the cosmic ray proton spectrum at high energies (Ormes and Balasubrahmanyan, private communication.) The model also requires confinement of a young component to a spiral arm region containing the Sun. Such a picture does not appear to be consistent with analysis of the non-thermal radio data[12] or a detailed analysis of the galactic γ-ray data[13]. Finally, it should be stressed that there are no physical reasons that the Galaxy should be substantially closed to cosmic-ray leakage. It thus appears questionable to invoke this model. In any case, this model will not account for all of the data.

3. Other Propagation Models We show in Figure 1, the prediction of Protheroe[5] for the leaky box model using the energy dependence of the mean escape length obtained from secondary to primary ratios[14] (7±1 g/cm^2 of interstellar matter below a rigidity, R, of ∿ 4 GV/c; $(7\pm1)(R/4)^{-0.4\pm0.1}$ g/cm^2 above 4 GV/c). The spectrum of an additional primary antiproton component making up the deficit p̄ flux would have to have roughly the same shape as the galactic proton spectrum. The ratio

of the extragalactic $\bar{p}$ flux to the galactic proton flux would then be $(3.2\pm0.7)\times10^{-4}$. This is plotted as the heavy dashed line in Figure 1. The reduction in the $\bar{p}/p$ ratio below this value at low energies is due to the combined effects of "galactic modulation" (ionization energy losses, nuclear interactions and $\bar{p}$ annihilation) and solar modulation assuming a mean energy loss in the heliosphere of [illegible]00 MeV. For galactic wind models[15], energy losses would be greater and the reduction enhanced. The $\bar{p}/p$ ratio for the sum of this extragalactic component plus the secondary (leaky box model) component is shown by the heavy line of Figure 1.

The inconsistency of the observed cosmic ray antiproton spectrum and intensity with the calculated secondary flux, as well as the fact that $\bar{p}/p \approx$ const. independent of energy, are both indications of a possible primary extragalactic origin[1,6]. Studies of galactic γ-radiation indicate that the bulk of the cosmic radiation is of galactic origin[16]. Baryon symmetric domain cosmology provides a scenario wherein half of the galaxies in the universe may be made of antimatter[17]. This cosmology has been given a new basis within the framework of grand unified gauge theory[6,18]. Since the γ-ray background observations indicate that matter and antimatter regions in the universe are separated on at least a galactic scale, a small extragalactic cosmic ray flux containing $\bar{p}$'s would be consistent with this cosmology. Using rough energetics arguments[19,20] one can estimate that leakage from normal galaxies would produce an extragalactic cosmic ray component with a flux $(I(ex)/I(gal))_{NG} \equiv \xi(NG) \approx 10^{-5}$-$10^{-4}$. For active galaxies, these estimates yield $\xi(AG) \approx 10^{-3}$. If we assume that half of the extragalactic flux is from antimatter sources, the resulting estimate for $\bar{p}/p \approx {}^1/_2\,\xi(AG) \approx 5\times10^{-4}$ is quite close to the measured values (see Fig. 1). The best 95% confidence upper limits at present are $\bar{\alpha}/\alpha < 1.5\times10^{-4}$ at 4.33 GeV/c[21] barely consistent with $\bar{\alpha}/\alpha \approx \bar{p}/p$, and $\bar{\alpha}/\alpha \lesssim 2.2\times10^{-5}$ in the low energy range of 130-370 MeV/nucleon[2] indicating that $\bar{\alpha}/\alpha \lesssim \bar{p}/p$ in this energy range. This latter upper limit is consistent with $\bar{\alpha}/\alpha = \xi(NG)/2$. Note that we can only argue that $\bar{\alpha}/\alpha = \bar{p}/p$ for cosmic ray production in normal galaxies, since we are comparing extragalactic fluxes with fluxes produced by processes in our own galaxy. It is conceivable that cosmic-ray α's produced in the cores or jets of active galaxies are broken up by collisions with matter or photons. Thus, the observed $\bar{p}$'s could come from active antimatter galaxies without accompanying α's, but with the expected $\bar{\alpha}/\alpha \sim 10^{-5}$ from normal antimatter galaxies. In this case, future cosmic-ray experiments may soon detect $\bar{\alpha}$'s!

In a matter-antimatter symmetric domain cosmology it is possible for the helium formed in the first three minutes of the big-bang to have been partially or totally destroyed by photodisintegration by annihilation γ-rays[22,23]. If this is indeed the case, active galaxies and quasars during a "bright phase"[24] may have had very little He to accelerate. The maximum distance extragalactic cosmic rays diffuse in time t_u is $R(max) \approx (2Dt_u)^{1/2}$ where $D = (1/3)\,\ell v$ is the diffusion coefficient and $t(u) \sim 10^{10}$ years[20]. Since $v \sim 10^{10}$ cm s^{-1} the largest uncertainty lies with the determination of the length scale. The length ℓ is of the order of the scale of inhomogeneity of the intergalactic magnetic field, which is not less than the intergalactic particle mean free path $\ell \sim (n\sigma)^{-1}$. In an ionized gas $\sigma \approx 3\times10^{-6}T^{-2}\ln(600T/n_e^{1/3})$, which for

$T \sim 10^6$K and $n_e \sim 10^{-7}$- 10^{-5}cm^{-3} gives $\ell \approx 10^{21}$-10^{23}cm. If the cosmic X-ray background is attributed to thermal emission, the corresponding temperature would then be 10^8K[25]. Hence $\ell > 10^{23}$cm is not an unreasonable estimate. Thus, extragalactic cosmic rays can arrive from other clusters or superclusters which may consist of antimatter galaxies and contain cosmic ray sources.

4. Conclusion The estimates presented here suggest that present upper limits on the flux of $\bar{\alpha}$'s may be close to detection levels. We suggest that future $\bar{\alpha}$ searches should be carried out. Such observations could provide important knowledge regarding physics at ultrahigh energy[18,26], the early universe, and extragalactic cosmic ray energetics and propagation.

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